UNIVERSITY OF LIVERPOOL

PHYS 379

# PROJECT (BSC)

## Industrial Application of Electron Beam - Crosslinking


**Name: Nur Ashiela Abdul Manaf**

**Student ID: 200734837**

**Course: F300**

**Supervisor: Dr. Kai Hock**

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## 1.0 Abstract

This project is intended to be the literature review of the industrial application of electron beams in crosslinking process. The history of electron beam crosslinking application progressed from first idea of replacement of traditional technique until the modern development into new product has been reviewed. One of the chapters will be discussed about the chemical and biological process of process crosslinking on how electron beam change the properties of the material to produce a high quality of end-product. They are different end use products that use the crosslinking process such as wire and cable insulation, heat shrinkable product, plastic form and tire components. All of this process is usually using the medium energy accelerator with the range energy from 300keV to 5MeV. The electron beam processing system can be broken down into a number of sub systems and it is important to understand the coherent of the process in order to detect the possible area of development of the machine. The proposed suggestion of improvement is made and back up with the solid argument for the better productivity of the machine, excels quality of the product and the lower financially cost.

## 2.0 Objective

This project is a survey on the literature of industrial electron beam machines and a study on how electron beam works in selected application. The application that has been chosen is application of electron beam in crosslinking process. The main aim of the project is a review on application of electron beams in cross linking and to identify potential areas in need of further research and development. The project is not just a literature survey but also propose new ideas for research and development (RND). Proposing new ideas is not about making a few suggestions it also will be backed up by strong reasons based on what have been learnt from the materials and what is physically and financially possible.

Objectives of the project:

1) To study on how electron beams are used in cross linking.

2) To research on how electron beam machines works for the application.

3) To research on possible area of development of the machines for greater efficiency and lower cost.

## 3.0 Introduction

Industrial application of electron beams has been evolved for several decades from early 1930 and still expanding until now. Electron beam technology is a process for treating material with high energy electron produce by an accelerator to cause specific effects (Electron Beam Technology: Turning the corner towards suatainable indutrial applications, December 6-8, 1999). By using electron beam radiation processing, the chemical and physical properties of material is modifying in order to enhance the product quality of usefulness and value. Electron beam is an alternative of industry use of conventional method such a gamma ray or chemical additive. Other than concern about reliability and financing, application of electron beam also offers a conservation of energy and environmental friendly advantages.

Electron beams are widely used in industry for medical, environmental and material processing application. In medical industry, electron beam used for sterilization of medical equipment, radionuclide production and other development of technology while water treatment, preserving food and pollution prevention is the example of electron beam application for environmental industry. The major application of electron beam is in material processing industry such as grafting, curing, degrading and crosslinking. Crosslinking is the main process of modification properties that used electron beam technology that will be discuss further in this project.

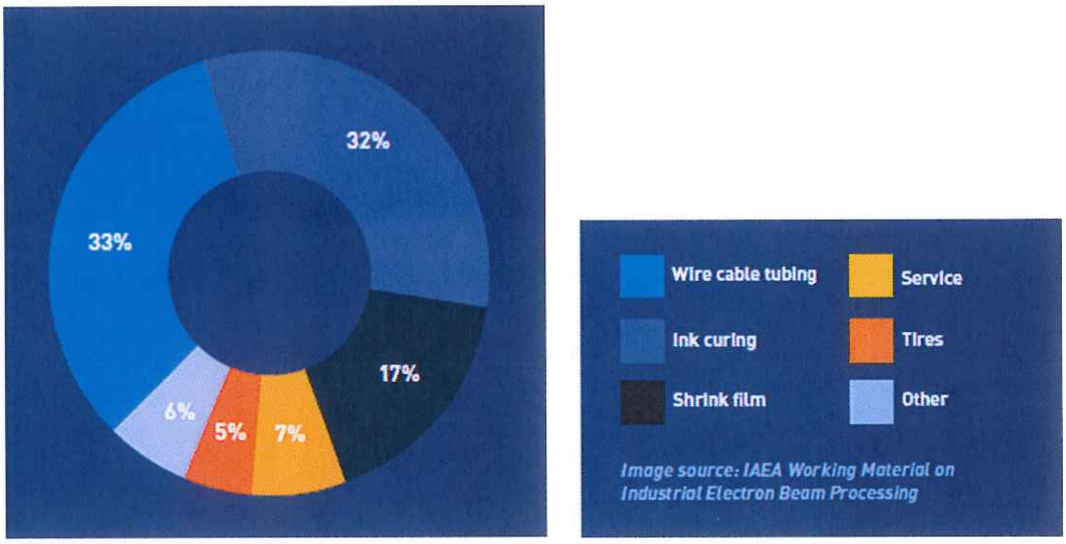


*Figure 1: Industrial Electron Beam Accelerator End-Use Market* (Accelerators for America's Future, June 2010)

According to the pie chart in the figure 1, about 55% of the end-use market of industrial electron beam accelerator is come from crosslinking process which is wire and cable tubing, shrink film and tires. It proven the statement that crosslinking is important and widely used in the electron beam technology for industrial. Approximately, 1700 high-current of industrial electron beam accelerator produce 10 billion dollars of value added product in diverse market areas world-wide. (Accelerators for America's Future, June 2010)

Historical development of application of electron beam in crosslinking is started in May, 1933 by Goodrich Company that introduced the early patent on an industrial use of electron beams processing to vulcanize natural rubber. (Industrial Radiation Processing with Electron Beam and X-rays, 1 May 2011). Then, in early 1950's, Malcolm Dole and Arthur Charlesby discover that major commercial end-uses if ionization radiation from electron beams. They found polyethylene (PE) upon exposure to ionizing radiation. Paul Cook from Raychem Corporation take an advantage of crosslinking PE for wire and cable insulation in 1957 followed by Bill Baird from Cryovac Division that developed process of heat shrinkable film for food packaging (Prospect and Challenge forindustrial use EB accelerator, 2009). The technology of crosslinking by electron beam growth radically and replace the conventional method of crosslinking.

The industrial electron beam accelerator has been designed customised for specific application. Different type of crosslinking demand a specification of accelerator that should be built and installed tailored to individual needs. The features of electron beam accelerator attractive for industrial used because of simple and safe operation. The accelerator produces a high radiation output at affordable cost. Many kind of research is going on to achieve the best quality of end product while reduce the power and energy consumption of the process. The literature of industrial of application of electron beam in crosslinking is reviewed to identify potential area of research and development of specified accelerator for greater efficiency and lower cost of production.

## 4.0 Crosslinking

Crosslinking process began about 80 years ago which a play an important role in a material processing industry of polymer. The aim of this process is to crosslink plastic material to improve product and material performance. Crosslinking is the process where the long chain of polymers is linked together increasing the molecular mass of the polymer as a result (Radiation Crosslinking of Polymers, 2010) . The three dimensional network structure form from the linear polymer. There are different techniques of crosslinking process depend on the polymer itself. Peroxide and Silane technique is the conventional method of crosslinking that needed chemical additives is but the most cost-effective technique is using the radiation of electron beam.

### 4.1 Basic process of crosslinking

The diagram below show the basic technique of the electron beam radiation of crosslinking for a polyethylene polymer (PE);

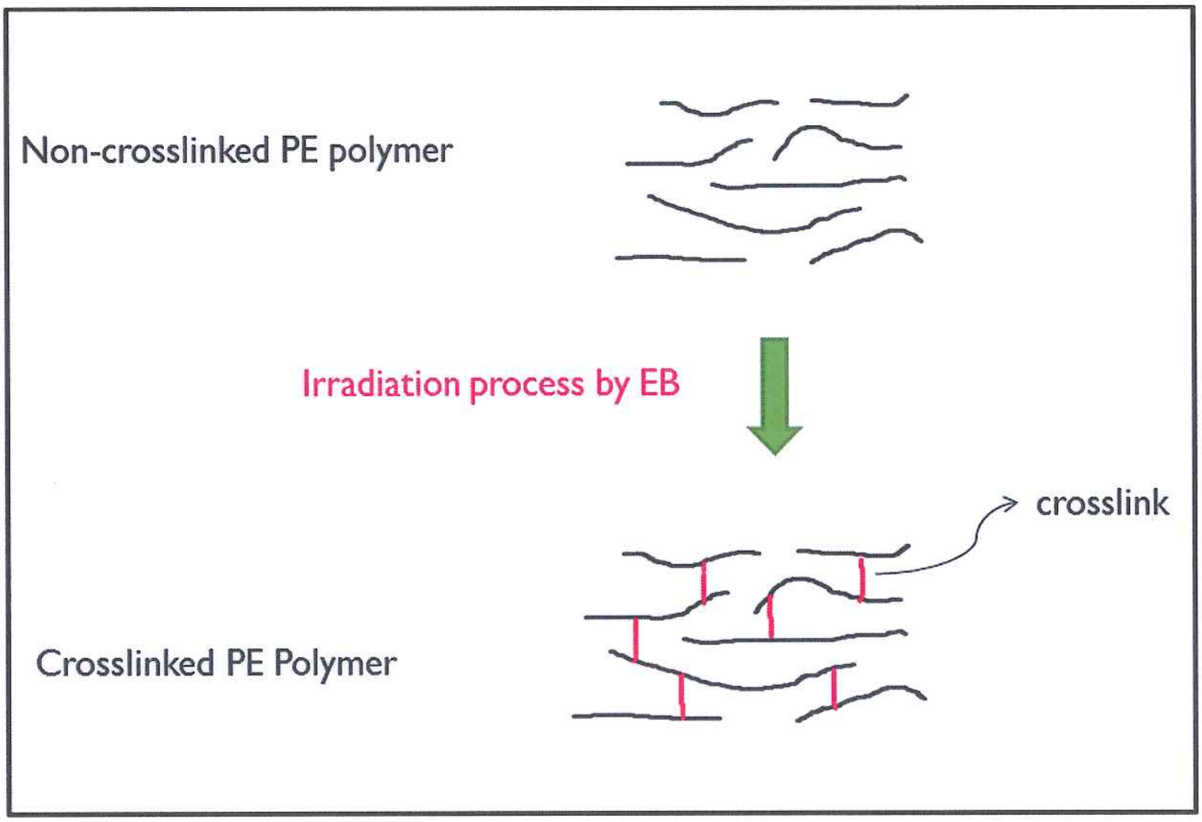


*Figure 2: Basic process of crosslinking*

The non-cross linked PE polymer strings are not linked to each other. The polymer is at thermoplastic state which is a long chain of polymer. The irradiation process by electron beam then creates the active sites on the adjacent chain of polymer which link to the another active sites of polymer. It formed a three dimension connection between long polymer chains which creates strengthened structure called 'crosslink'. As polymers are linked to each other, the chain is no longer slide pass each other and then changes the molecular structure of the polymer to become a thermosets material. The degree of crosslinking varies depending on number of links between each polymer chain.

The electron beam radiation process of crosslinking improved the thermal, mechanical and chemical properties of the polymer suitable for industrial product purposes. For the thermal properties, crosslinking processes provide the resistance to temperature for the cross-linked polymer. This statement is proven based on the diagram above;

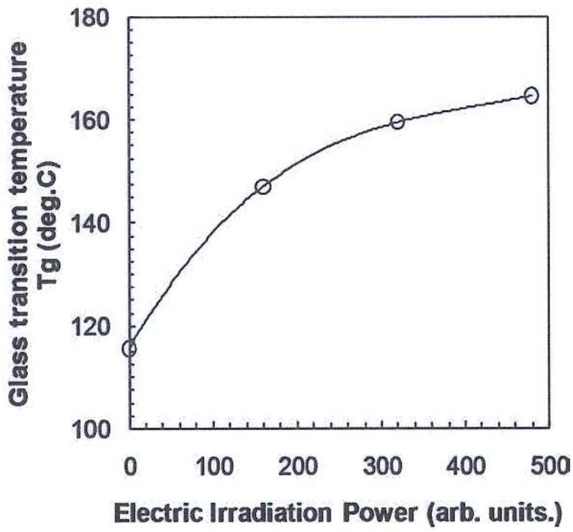


*Figure 3: Dependence of the glass-transition temperature on electron beam irradiation power* (Transparent Thermoplastic Resin with Electron Beam Cross-Linking, 2011)

The graph shows that the glass transition temperature increased when the polymer exposed to the increasing electron beam irradiation power (Transparent Thermoplastic Resin with Electron Beam Cross-Linking, 2011). Higher glass transition temperature means, the melting point of the material is increasing. So, the material or polymer can performed and no longer melt at higher temperature.

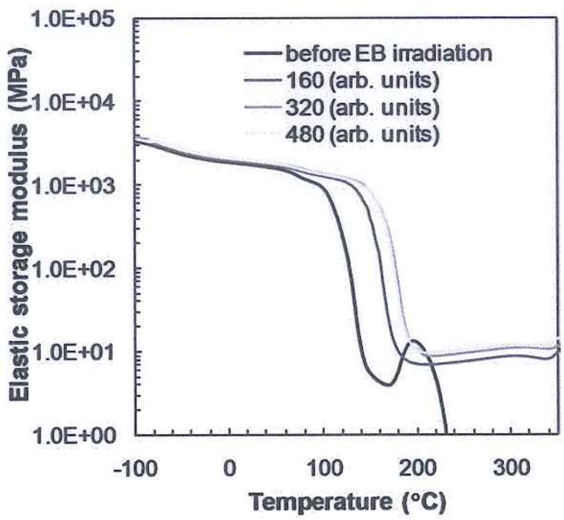


*Figure 4: Dependence of the elastic storage modulus on the electron beam irradiation power.* (Transparent Thermoplastic Resin with Electron Beam Cross-Linking, 2011)

Figure 4 shows the elastic storage modulus as a function of temperature before and after the polymer went through crosslinking process by electron beam radiation. From the line of before electron beam irradiation, the non-cross-linked polymer melts at about $160^0$C then show peak at $200^0$C. The peaks come from the process of recrystallization and then, the polymer loss the elastic storage modulus. After the electron beam irradiation process, the elastic modulus storage of the polymer became flattened at $200^0$C. This is show the rubber-like characteristic that brought to the conclusion of transformation from brittle to ductile state of the polymer (Transparent Thermoplastic Resin with Electron Beam Cross-Linking, 2011). The crosslinking process also improves the resistance of chemical of the cross-linked polymer due to lowered solubility in organic solvent (Radiation Crosslinking of Polymers, 2010).

## 4.2 Advantages of electron beam crosslinking

Electron beam crosslinking offers more advantages compared to the chemical crosslinking such as Peroxide and Silane technique. The table below show the technological comparison of crosslinking method of polymers;

| Crosslinking Method | | Radiation (EB) | Peroxide | Silane |
|---|---|---|---|---|
| Major products | | Wire & cable, tube, pipe, film, foam | Wire & cable, tube, pipe, foam | Wire & cable, pipe |
| Plastic | PE | ○ | ○ | ○ |
| | PP | ○ | △ | △ |
| | PVC | ○ | △ | △ |
| | Engineering plastics | ○ | × | × |
| | PTFE | ○ | × | × |
| | Fluoropolymer | ○ | ○ | △ |
| Cost of compounding | | Low | Medium | High |
| Shelf life of compound | | Long | Medium | Short |
| Product thickness restriction | | $<10$ cm | $>0.3$ mm | $>0.3$ mm |
| Rate of crosslinking | | High | Low | Low |
| Degree of crosslinking | | Medium | High | Low |

○ in practical use, △ technically possible but no practical example, × hard to apply.

*Table 1: The technological comparison of crosslinking method of polymers.* (Keizo Makuuchi, 2012)

The comparison of the different crosslinking method clearly illustrate that electron beam radiation is the best option and practical to use in the industrial application. The main advantage is fast cure time of production. As soon as the materials pass through the irradiation beam, the process is completed and the product is ready to use. Electron beam crosslinking is also inexpensive and economical compared to conventional method because electron beam compound is very simple and easy to produce. This method also good for environmental because do not require chemical additive thus solve unwanted reaction product problem. Degree of crosslinking can be easily controllable by amount of dose because electron beam delivered directly to the polymer. (Radiation Crosslinking of Polymers, 2010). This allows process to be precisely controlled and adjusted to meet the required product properties. High level of process control leads to the high quality of the end product.

### 4.3 Electron Beam Crosslinking End-Use Application

Crosslinking is the most successful application of electron beam in material processing industry because produces a lot of different commercial product that made of cross linkable plastic such as Polyethylene(PE), polyvinyl chloride (PVC), nylon (PA6, PA6-6, PA12, etc), and many more. There are examples of end-use application product that use electron beam crosslinking;

#### 4.3.1 Wire and Cable Insulation

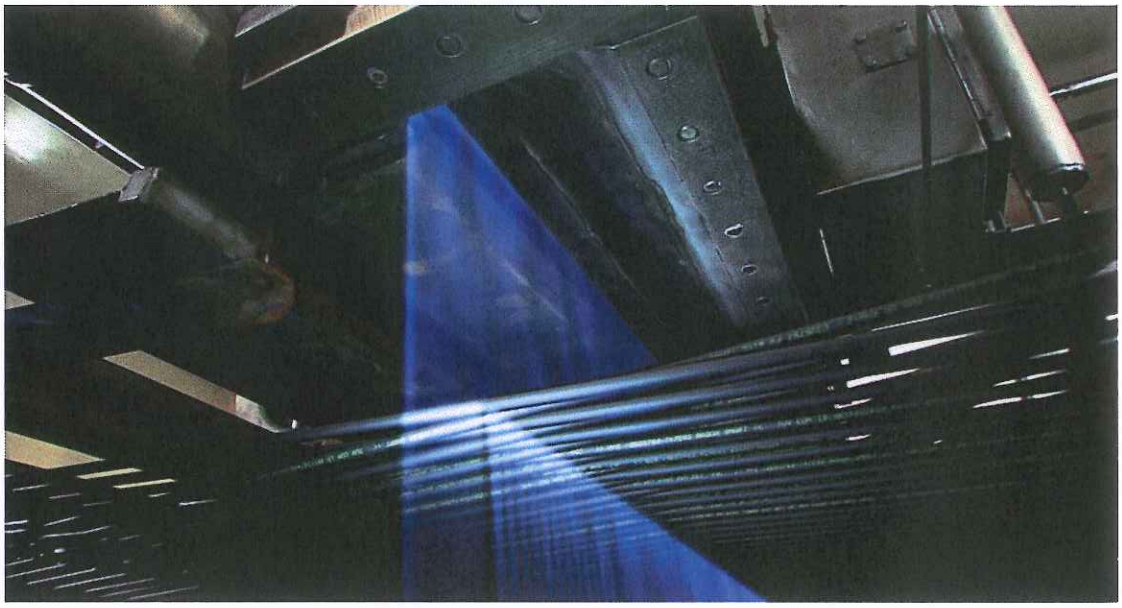

*Figure 5: Electron-beam crosslinking in cable production* (Electron-beam crosslinking technology, 2013)

The electron beam crosslinking of the insulation jacketing on wire and cable is one of the most well established industrial uses of electron beam processing (Industrial Radiation Processing with Electron Beam and X-rays, 1 May 2011). Wires jacketing that have been cross linked plays an important role as heat resistance insulator to keep the functionality of the wiring materials in severe and harsh environment. Cable insulator will retain its shape and not melting although surrounded by a high temperature condition such as in a short circuit accident and when been exposed to the flames. So, wire and cable can work safely under any circumstances since they have been widely used for electronic equipment and automobile industry. Despite from that, the improvement of chemical and mechanical properties of the cable insulator shown as it gives the resistance to solvent and corrosive chemical and increased the tensile strength in order to maintain the long term reliability of the cable.

### 4.3.2 Heat Shrinkable Product

Shrinkable products are the first cross linked products were used in industrial applications (Radiation Processing of Polymers, 2004). Shrink product can be divided in to two main product which are heat shrinkable film and heat shrinkable tubing as shown in the diagram below;

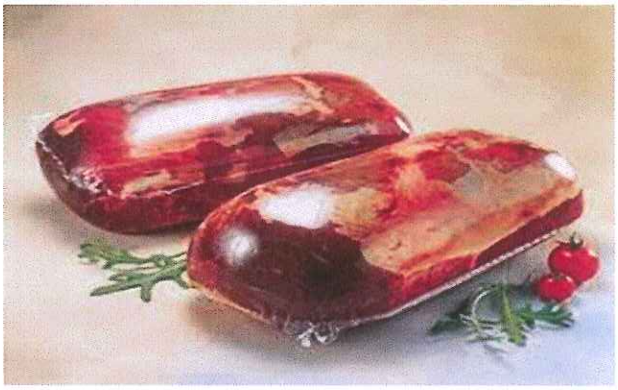

*Figure 6 : Heat shrinkable film* (tjskl.org.cn, 2011)

*Figure 7: Heat shrinkable tubing*

(Industrial Radiation Processing with Electron Beam and X-rays, 1 May 2011)

Production of heat shrinkable product is used a 'memory effect' technique. Cross linked material become elastic when heated above the melting temperature of crystalline zone, approximately $100^0$C (Industrial applications of electron accelerators, 2005). The product now can be expanded and stretch from original shape. Then, the product is cooled down to room temperature but the transformation is maintained .When the heat is apply again, the product remember its 'rubber-like' state and can shrink back to its original dimension (Radiation Processing of Polymers, 2004).

Heat shrinkable film or commonly known as shrink wrap practically used in food packaging. Electron beam tie the molecules of the plastic together and make the film tougher mechanically (Accelerators for America's Future, June 2010). As shown in the figure 6, the process started with placed the shrink film on top of the food. Then, when applying heat, the plastic shrink back to its original size and result in air-tight wrapping of the food. This will maintained the freshness of the food within a simple and safe process. The similar procedure happened in a making of heat shrinkable tubing that used to cover a wire connection. It follow the properties and purpose as wire jacketing but speciality to the tubing for corrosion protection of piping joints and wiring terminals as shown in the figure 7.

### 4.3.3 Plastic Foam

The technology of plastic foam was invented in Japan by Toray Industries Inc. and Sekisui Chemical Co. Ltd. which began the production of foamed polyethylene (PE) (Electron beam Processing System and Its Application, October 2012). They developed a Sekisui process to produce highly expanded plastic foams consisting of closed cell made of polyolefin (Keizo Makuuchi, 2012). The productions of plastic foam start by mixing the polymer, blowing agent and additive to perform extrusion process below the decomposition of the foaming agent. Next, the sheet produce is cross linked by electron beam to increase the viscosity of the polymer. Last but not least, it was heated to release gas from blowing agents and forms a bubble of polymer as we know as plastic foam. The common blowing agents used in this process is azodicarbonamide (ADCA, $H_2N\text{-}CO\text{-}N{=}N\text{-}CO\text{-}NH_2$) (Keizo Makuuchi, 2012).

The properties of foams depend on the type of polymer used, concentration of blowing agent and distribution of crosslinking. Crosslinking and foaming process can be performed separately in electron beam crosslinking method while it is possible to do in chemical crosslinking. This benefit allowed controllable of bubble fraction and produce a smooth surface and well defined closed cell foam structure. Plastic foam generally used for a safety and protection product such as athlete safety pads, helmet liner, automobile seat padding and also widely used in medical device industry.

*Figure 8: Medical devices and automotive uses of electron beam cross linked PE closed cell foams* (Industrial Radiation Processing with Electron Beam and X-rays, 1 May 2011)

### 4.3.4 Tire Components

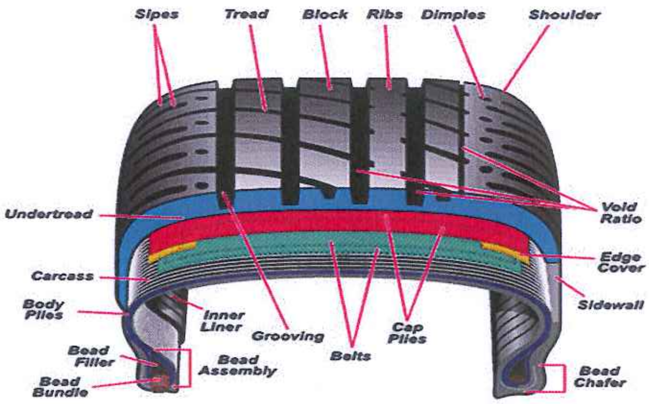


*Figure 9: The basic components of tire production* (Yokohama, 2013)

In Japan, Goodyear Corporate and The Firestone Tire & Rubber Co. started to use the technology that rubber material is irradiated to crosslink by electron beams for tire manufacturing (Electron beam Processing System and Its Application, October 2012). Tire components such as body ply, inner liner, belts, side wall and bead chafer need to exposed to the electron beam for partial radiation crosslinking process before its assembles to manufacture of tire through vulcanization process. The green strength of rubber material increased while maintain its thickness and dimension. These reduce the amount of rubber material use, then impact on cost reduction in production of tire. A saving of 0.29 dollar per tire is reported by applying electron accelerator irradiation in the factories because of reduction of thickness in tire manufacturing industry (Electron beam Processing System and Its Application, October 2012).

# 5.0 Electron Beam Accelerator

## 5.1 Classification of the accelerator

Accelerator is a device to accelerate electrons or ions to give energy (Electron beam Processing System and Its Application, October 2012). Radiation accelerator is commonly used in the industry processing for commercial purpose and electron beam is used as alternative to the use of gamma ray in the processing system of the accelerator. They are classification of industrial electron beam accelerator depends on the energy range of electron produced and the technique of the acceleration. The accelerator divide into three level of energy which is low energy, medium energy and high energy as shown in the table below;

| | **Low Energy** | **Medium Energy** | **High energy** |
|---|---|---|---|
| Energy range | 70 keV - 300 keV | 300 keV – 5 MeV | 5 MeV – 10 MeV |
| Features | Wide unscanned beam ≤ 3m | Scanned beams ≤ 3m | Linac of SRF |
| Current Application | • Curing of inks<br>• Crosslinking of polymers<br>• Surface sterilization<br>• Remediation of liquids and gases | • Crosslinking of wire and cable insulation<br>• Crosslink heat-shrinkable plastic tubing<br>• Manufactured od closed-cell foam<br>• Crosslink rubber<br>• Medical sterilization | • Bulk sterilization of medical devices<br>• Crosslinking thicker plastic |

*Table 1: Classification of Accelerator* (Accelerators for America's Future, June 2010)

The low energy accelerator use the energy range from 70- 300 keV is the most rapidly growing in industrial application of electron beam market because of the sufficiently low in voltage. The current niche market that used this kind of accelerators was curing in inks, crosslinking of polymers, surface sterilization and remediation of liquids and gases. This accelerator is known as non-scanning type of electron processing which is used an electron wide area curtain system. The source is linear source rather than point source, so no scanning is necessary (Electron Beam Accelerator, 2009). It was like a wide shower of electron beam with maximum 3m length to cover necessary area of the product. The non-scanning type is applied to devices with a low energy of 300 keV or less because of the constructional limitation (Electron beam Processing System and Its Application, October 2012).

The most common of accelerator of industrial used is medium energy electron beam accelerator with energy range from 300 keV up to 5 MeV. The basic feature of medium accelerator is follow the the cathode ray tube system of television. The devices are commonly based on transformer type to produce high voltage direct –current power supply and acceleration tube in which electron from small heated cathode are accelerated to produce scanned beams with wide up to 3m (Development of Family of Low,Medium and High Energy of Electron Beam Accelerator, 2003). Almost of the crosslinking application of electron beam is operated under medium energy of accelerator used such as wire and cable insulation, heat shrinkable film and tubing, closed cell foam, rubber of tire component and also used for medical sterilization in medical industry.

Last but not least, high energy electron beam accelerator that custom made for the specific application like crosslinking for thicker plastic and bulk sterilization of medical devices. At this point in processing industry, they are two types of high energy accelerator used in industry which is microwave linear accelerator (Linac) or radio frequency devices (SRF). High energy accelerator do not used a direct current to extracted electron beam but instead used special devices of Linac and SRF pulsed type to produce pulsed the output beam naturally. The limited peak energy of the accelerator for industrial use is 10 MeV to avoid inducing radioactivity in treated material (Accelerators for America's Future, June 2010). Linac's accelerator is growing rapidly in industrial field because the research shown that linacs have relatively modest energy conversation energy approximately about 30% of input power to beam output.

### 5.2 Electron Accelerator for Crosslinking

Most of the polymer crosslinking operations are used medium energy direct current accelerator. Table 2 below shown the electron energy needed and the typical penetration of different type of crosslinking process;

| Type of Crosslinking | Electron energy | Typical penetration |
|---|---|---|
| Shrink Product | 300 – 800 keV | 2mm |
| Plastic Foam | 0.5 – 1.0 Mev | 5mm |
| Wire Cable | 0.4 – 3.0 MeV | 10mm |
| Tire Components | 0.8 – 3.0 MeV | 12mm |

*Table 2: Electron energy and typical penetration of crosslinking process* (Industrial Radiation Processing with Electron Beam, 2011)

Electron beam crosslinking process usually operated with electron energies from the range 0.3 to 1.5 MeV. Some of the machines can use higher energy until maximum 3MeV depends on the thickness, density and penetration needed of the material of the polymer to change the composition in order to produce desired product. Although it is used the medium electron energy, this machine can provide high beam current that is essential to generate high dose rates which is needed in the industrial production of crosslinking process. The electron beam current is usually in the range of 25 to 100mA. The calculation of current beam is related to the absorbed dose and line speed as being discussed in the previous chapter (Electron Beam Crosslinking of Wire and Cable Insulation, 2009). The beam width or scanning width also the main factor of the accelerator that should be considered in the suitable accelerator for specific type of the crosslinking process. The normal scanning scan width is about 0.5 to 2m determined by the conveyer system and scanning chamber of the devices. Five machines or accelerator that attains medium energy and high beam current, mainly used in crosslinking process is stated in the table below;

| Type | Manufacture | Max. Voltage (kV) | Max. Current (mA) | Scan Width (m) |
|---|---|---|---|---|
| Broadbeam LE Series, 300keV | PCT Engineering System | 150 | 65 | 1.8 |
| EC- Scanner, 400 keV | AB Crosslinking | 250 | 30 | 1.25 |
| Easy e-Beam, 800keV | IBA Industrial | 800 | 100 | 0.91 |
| Air Core Transformer HPIA, 2.5 MeV | BINP (Institute of Nuclear Physics) | 1000 | 50 | 1.4 |
| Dynamitron , 3MeV | IBA Industrial | 1100 | 50 | 1.2 |

*Table 3: Electron Beam Accelerator used in crosslinking process*

Broadbeam LE accelerator with 300keV of energy is manufacture by PCT Engineering System with operating voltage range from 70 to 150kV (2010-2013). PCT Engineering System has upgrade its low energy equipment to make it can be used in different type of application rather than printing. So, LE Series is accelerator that widespread with lower power consumption, simple maintenance and operation. This accelerator is design for different type of crosslinking application with scan width up to 1.8m.

*Figure 10: Broadbeam LE Series* (2010-2013)

Crosslinking AB has produced EC-Scanner, 400keV with maximum voltage of 250kVand maximum voltage of 30mA (Industrial Application of Electron Beam Curing in the Fields of Coatings, 2003). EC- Scanner is tailored made for the film and tubing crosslinking application with scan width of 1.25m.

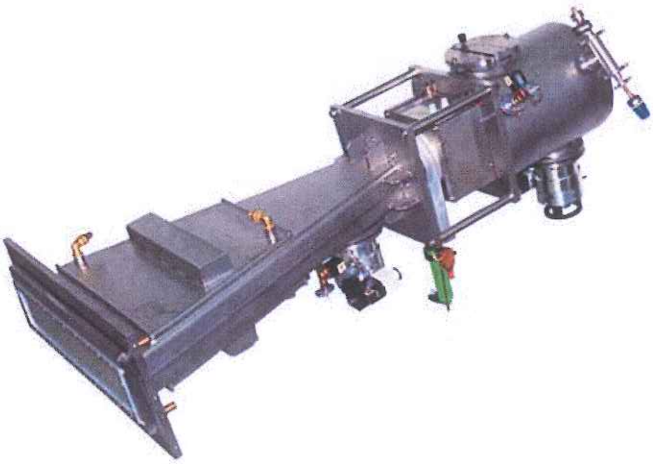

*Figure 11: EC-Scanner, 400keV* (Industrial Application of Electron Beam Curing in the Fields of Coatings, 2003)

IBA Industrial's Easy e-Beam, 800 keV self-shielded of high current from 70 toml00mA is manufactured specific for the development of the insulated wire, cable and plastic tubing of electron beam crosslinking process. Instead of transformer as high voltage generator, it used a radio frequency oscillator and then converts at frequency of 100 kHz to high voltage direct current (The IBA Easy-E-Beam Integrated Processing System, 2011).

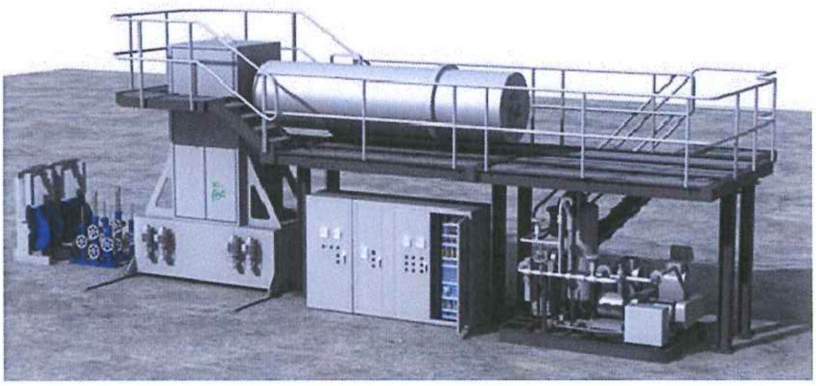

*Figure 12: Easy e- Beam , 800keV* (Industrial Radiation Processing with Electron Beam, 2011)

Air Core Transformer High Power Industrial Electron Accelerator (HPIA), 2.5 MeV is another accelerator that manufactured for the specification of wire and cable insulation crosslinking process. The power supply is high current up to 1100kV with only produce beam current of 50mA and scan width about 1.4 m. The high voltage rectifier is based on the Air Core Transformer (ACT) (High Power Industrial Electron Accelerator, 2007). This accelerator is build up by the Institute of Nuclear Physics, Russia (BINP).

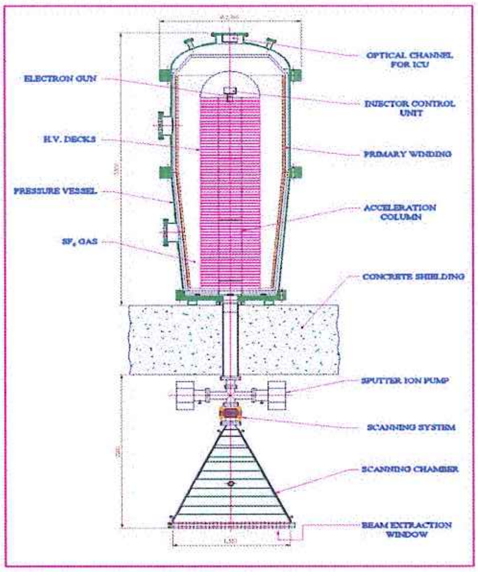


*Figure 13: Air Core Transformer (HPIA), 2.5 MeV* (High Power Industrial Electron Accelerator, 2007)

Dynamitron, 3MeV is developed by the M.R Cleland with association with IBA Industrial Inc. (Industrial applications of electron accelerators, 2005). It was a multi-purpose accelerator from crosslinking, degradation and colouring of diamonds but the most of this accelerator used in the crosslinking process of tire components and wire insulation.

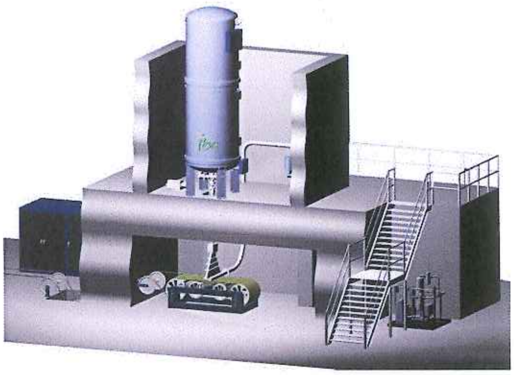

*Figure 14: Dynamitron, 3MeV* (Industrial applications of electron accelerators, 2005)

# 6.0 Electron Beam Processing System

## 6.1 Principle of Acceleration

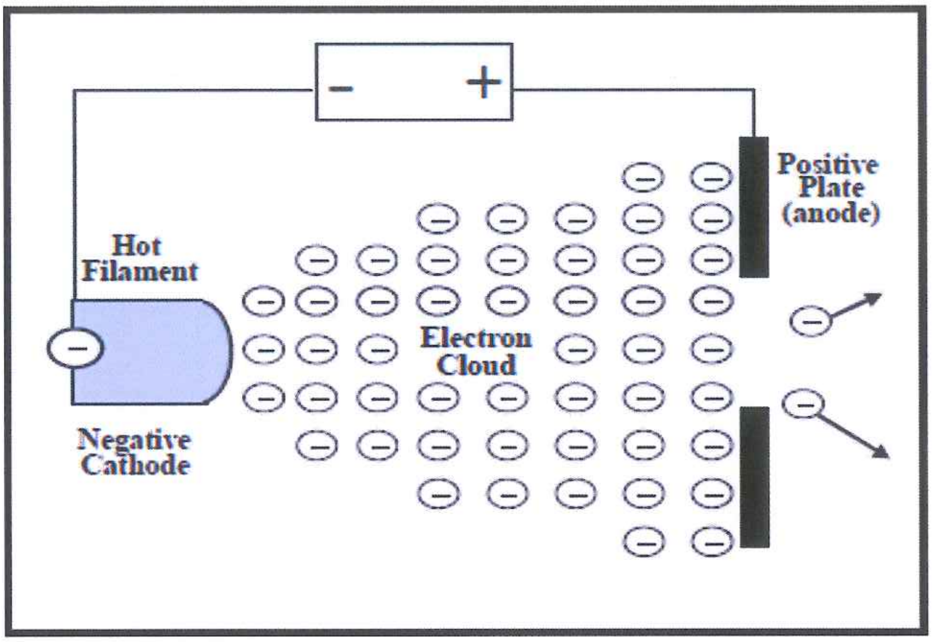


*Figure 15: Free electron generation* (ELectron Beam Technology , 1999)

Figure 15 above show the simple free electron generation of the electron beam. The principal of acceleration is the basic system to produce an electron beam and accelerated them in the electron accelerator. The tungsten filament which is metal is containing of full of static electron. When the filament is heated at the negative cathode, electron will be shaken and then emitted as a free electron which is negatively charged after enough energy is received by the electron. This is called as thermionic emission. Next, the free electron flow towards anode because of positive electric potential. The electrons accelerated by electric field given by the power source such as direct current high voltage and then gain energy in electron volt (eV). The accelerated electrons escape through the window and proceed towards the target material.

## 6.2 Electron Beam Processing System

Electron beam processing system is a system in which electrons are accelerated and given energy to be irradiated to target material (Electron beam Processing System and Its Application, October 2012). The processing system of electron beam can be broken down in to a number of sub system which are power supply unit, electron accelerator tube, scanning system, irradiation window, vacuum system, product handling system and last but not least the safety system. The basic of the schematic diagram of the scanning type of accelerator is shown in the diagram below;

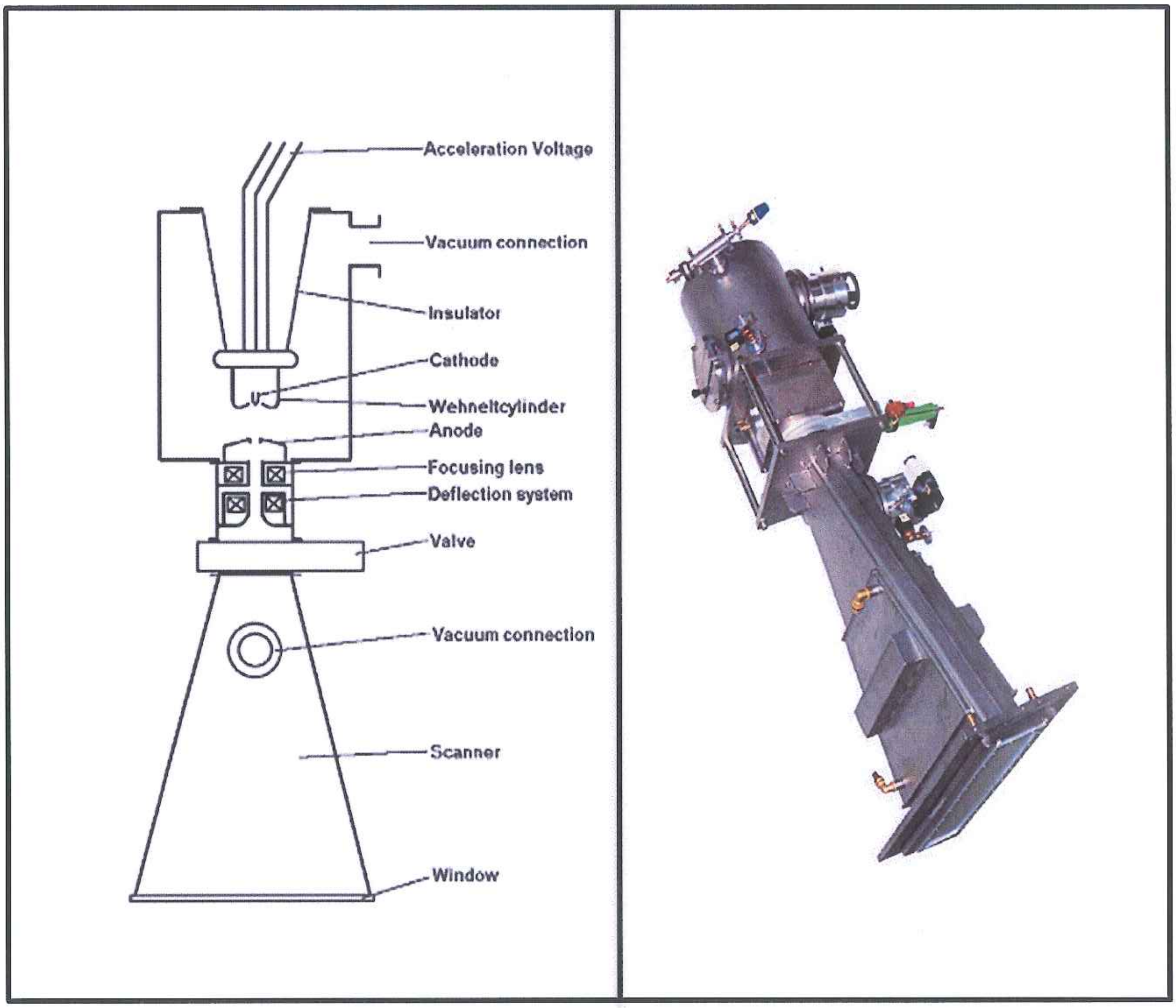


*Figure 16: Schematic diagram of the basic scanning type of accelerator* (Industrial Application of Electron Beam Curing in the Fields of Coatings, 2003)

### 6.2.1 Power Supply Unit

Power supply unit is the most important part to generate high voltage of direct current. High voltage rectifier or generator has been built and designed follow the specification of the accelerator commonly based on the transformer type. Coil wounded transformer are used to provide the voltage. The power level of the accelerator is the key to determine how larger of transformer needed for every machine depending on the high current production of the transformer. For example, Air Core Transformer HPIA, 2.5 MeV used the high voltage rectifier based on the Air Core Transformer (ACT) which has water-cooled primary winding and epoxy moulded multi section secondary winding (High Power Industrial Electron Accelerator, 2007). The transformer can be located inside the accelerator or can be connected to accelerator by high voltage cable. In case of Easy e-Beam, 800keV, different technique is implement which is using a high generator that convert radio frequency (RF) to high voltage direct-current. A radio frequency oscillator transformed three phase line power into single phase RF power for the high voltage generating system (Easy-e- Beam, 2008). The complete power supply need to locate in a pressure vessel filled with sulphur hexafluoride (SF6) gas as a coolant or insulator.

*Figure 17: Radio Frequency Oscillator of Easy e-Beam accelerator*

(Easy-e- Beam, 2008)

*Figure 18: High voltage generator (transformer based) of HPIA*

(Electron-beam crosslinking technology, 2013)

### 6.2.2 Electron Accelerator Tube

The electron accelerator or electron gun is usually located inside the high voltage vacuum. The main function of accelerator tube is to generate electron an accelerated them as discussed in the last section about the principle of acceleration. The free electron generation is called as filament system where consist of single or multiple cathode. The single cathode is the continuous long filament with approximate width of application area while the multiply cathode made of many short filament, connected to each other in parallel (Electron Beam Accelerator, 2009). The advantage of using multiple cathodes is the beam of electron produce is broadening compare to single cathode where the electron showers uniformly across the given area. The quality of production of electron depends with the temperature of filament. The part of accelerator tube is consisting of stack of metallic disc separated by glass or ceramic rings (Electron-beam crosslinking technology, 2013). The purpose of the design is to ensure that high voltage evenly distributed along the length of tube. The example of accelerator tube is shown in the diagram below;

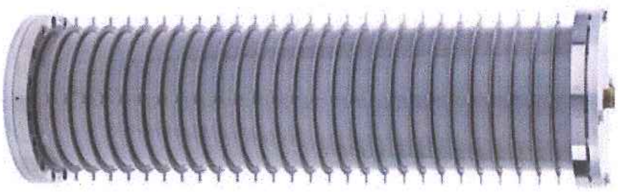

*Figure 19: Electron Accelerator Tube* (Electron-beam crosslinking technology, 2013)

### 6.2.3 Scanning System

According to the schematic diagram of accelerator in Figure 11 above, the scanning system is contain of focusing lens, deflection system, valve and the scanning chamber and irradiation window that all working under influence of magnetic field. The focusing lenses provided in the lower end of the tube to control the beam aperture (High Power Industrial Electron Accelerator, 2007). The deflection system is made by a set of magnet with a set of correction cork that deflects the electron beam through specific angle according to the design of the machine. The waveform of magnetic field in the scanning magnet is essentially in triangular form to provide uniform absorbed dose across the width of product handling fixture (The IBA Easy-E-Beam Integrated Processing System, 2011). This kind of scanning chamber also been built to allow electron beam scanned precisely for required width at target product area. The last part of scanning system is the irradiation window where the place of

electron beam escaped to the material. Irradiation window is usually made by a thin foil of titanium approximately about 10μm thickness for beam extraction (Industrial Radiation Processing with Electron Beam, 2011). The window must be thin enough to allow accelerated electron penetrated it easily and reduce the heat produced by lost energy of electron while pass the window.

### 6.2.4 Vacuum System

Vacuum system is important to prevent accelerated electron from collide with air molecules and avoid filament from burn out. So, vacuum pump is necessary to put in the accelerated tube and scanning chamber. The vacuum system should provide a sufficient pumping speed so that, the overall length of the tube and chamber is keep at high vacuum. Ions pumps are used to monitoring the vacuum condition.

### 6.2.5 Product Handling System

Product handling systems consist of two parts. The first part is the control unit which are the computerised or PC based control system. The task of this control unit is to set and monitoring the quality of the product. All the process variables such as absorbed dose, product speed, scanning amplitude, temperature and other can be controlled and manipulated through one control system. It also can shoe the status of the operation or critical process condition when there are any problems inside the machine. The control unit is designed tailored to the specific accelerator or company that using that device.

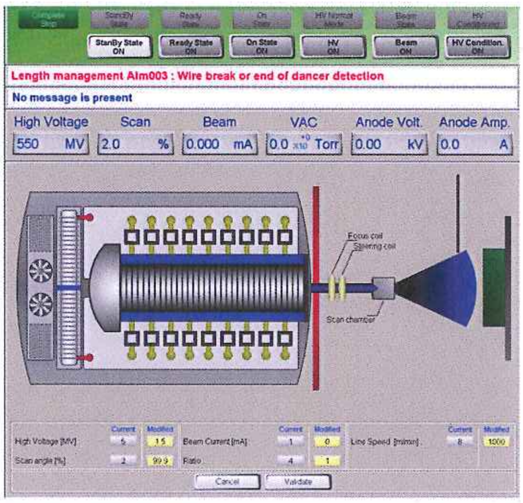


*Figure 20: Example of PC control system of Easy e-Beam*

(The IBA Easy-E-Beam Integrated Processing System, 2011)

The transportation device is the second part of product handling system. This is the method of travel product in and out under the beam extraction. There are lot of technique of transportation device from a simplest roller to the most complex conveyer system. Product size and thickness, geometry and batch size need to be consider to select the best transportation device. The aim of great transportation device is to delivered product with most uniform absorbed dose of electron of electron beam with minimum loses.

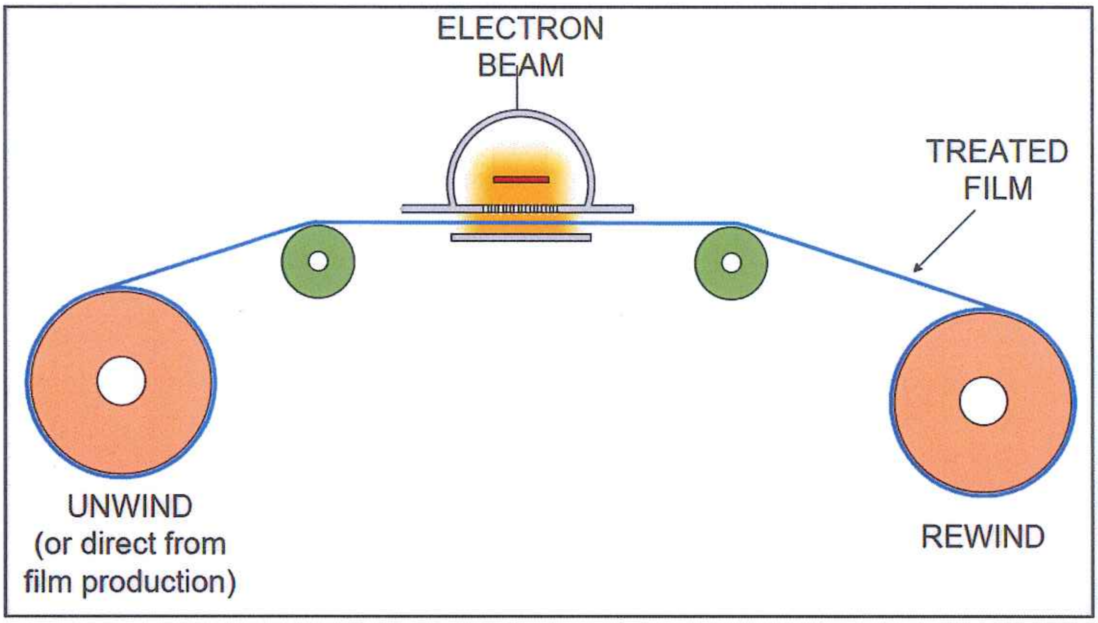


*Figure 21: Example of transportaion device of film crosslinking (Simple roller)*

(Electron Beam Technology for Converting Applications, 2006)

### 6.2.6 Safety System

When high energy electron is hitting the target material, the radiations of x-ray are possible to generate. Although only small quantity of radiation emission, it is crucial to ensure the accelerator prepared with the shielding for protection for the workers. Most of the accelerators are self-shielded because they are made from lead, steel or concrete. Electron beam accelerator equipped with x-ray detection devices which will read the background level and will be interlocked and shut down the operation of accelerator when there are increased level of x-ray detected (Electron Beam Accelerator, 2009).

### 6.3 Electron Beam Process Parameter

Process variables are important to identify the control of any process in order to predict the production and quality of the end product. There are lot of parameter that influences the process but can be ignored because its only affects a small percentage of end products. The main process parameter is discussed below;

#### 6.3.1 Absorbed Dose

Absorbed dose, D is the amount of energy which a material absorbs from radiation when irradiated which a deposited into a specific mass of material (Electron beam Processing System and Its Application, October 2012). The unit of absorbed dose is in gray (Gy) or energy absorption per unit mass of material (J/kg).

$$D = k \cdot \frac{I}{v}$$

(Industrial Application of Electron Beam Curing in the Fields of Coatings, 2003)

where, I = electron beam current (mA)

v = line speed (m/mins)

k = production constant

The typical absorbed dose requirement in crosslinking polymer is about 50 to 150kGy (Electron Beam Crosslinking of Wire and Cable Insulation, 2009).The production constant or equipment factor, k is derived from the distant to product, beam geography and the scan width of the accelerator. The equation also shows that the absorbed dose directly proportional to the electron beam current.

### 6.3.2 Electron Beam Energy

The penetration of high energy electron beams in irradiated material increases linearly with the incident energy (Industrial applications of electron accelerators, 2005). Beam energy is classified as a mono-energetic which means the energy particles confined to an extremely narrow range. The electron energy deposition, D(e) is the energy deposited per electron per unit area density. It's all about the collision of the incident electron with atomic electron of the target material which is important to calculate how deep the energy will be penetrate into the material. The graph below show the electron energy deposition against depth of penetration in terms of thickness x volume of density in unit of area density (g/cm$^2$) at various incident electron energy from 1.0 Mev until 3.0 Mev;

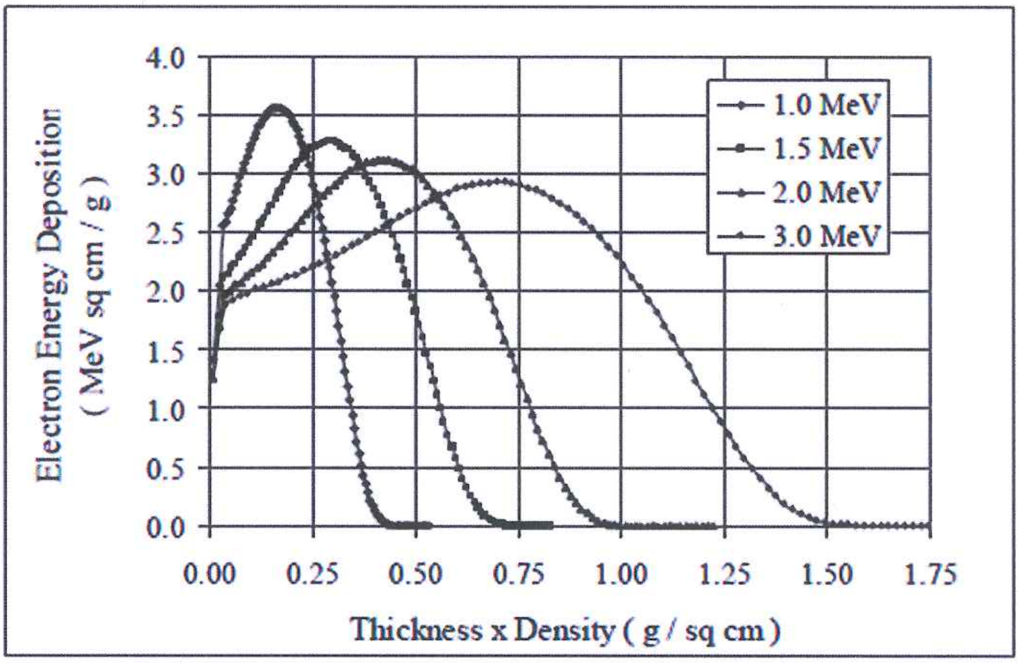


*Figure 22: Electron energy deposition vs. thickness x density in polyethylene at 1.0 to 3,0 MeV incident electron energy* (Industrial applications of electron accelerators, 2005).

### 6.3.3 Line speed

Line speed is show the processing rate of the material under the beam. Lime speed increased with the increased of beam current and number of product passes the beam but decreased with the increasing of beam width and absorbed dose (Electron Beam Crosslinking of Wire and Cable Insulation, 2009).

$$v = \frac{6.0\ D(e) I\ N}{WD}$$

(Electron Beam Crosslinking of Wire and Cable Insulation, 2009)

where D(e) = energy deposition per electron in MeV per unit are density

I = electron beam current (mA)

N = number of passes through the beam

W = width of the scanning beam (m)

D = total absorbed dose (kGy)

## 7.0 RND, Further Improvement

The accelerator or the machines that have been used in the crosslinking process in the industrial market have been developed drastically through the year. A lot of research and development in this area have been done in order to optimize the process and produce better product in terms of quality and reliability. Despite of the technology that can be upgraded and installed to enhance the productivity of the future needs, the time and cost effective measurement must be taken into account. The main aim is to ensure the electron beam provided is consistent with requirement of the product in order to make a full use of the parameter of the accelerator such as the beam energy and voltage. This is important to increase the efficiency of the device to reduce the processing cost and increase the production of the end-product.

### 7.1 3D Monte Carlo Simulation

The Monte Carlo Simulation EBXLINK3D has been developed to address the needs for dose calculations and optimizations of complex 3D radiation processes (Quantitative Dosimetry Simulation Tools, 2012). The simulation is consisting of the mathematical model of analytical formula that can aid the design process in order to build of prototype before it can be implemented to the machine. This simulation is viable and practical to minimize the possibility of human error while use the real time experimental technique that will take a longer time to come out with final result. The design can be built tailored to the original device to ensure the result shown is consistent with the actual accelerator and material. The diagram below show the graphic simulation of the single or double-scanner electron accelerators;

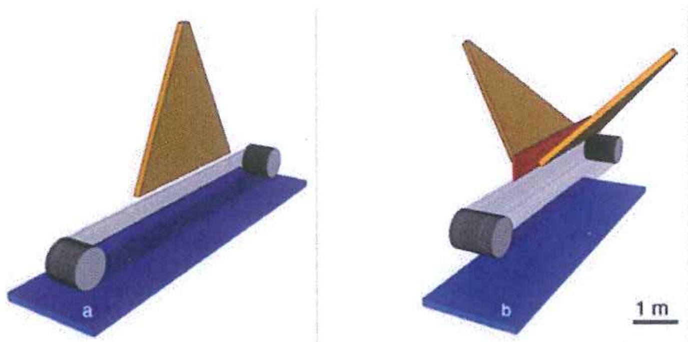


*Figure 23: Examples of simulation models for single (a) and double scanner (b) accelerators with multi pass system handling (racetrack)* (Electron-beam crosslinking technology, 2013)

## 7.2 Optimization of the Accelerator

All the parameter and equipment of electron beam processing system of the accelerator can be taken into account such as geometry of the material, distance to product, the angle of scan system, sided of the irradiation process and others in order to optimize the production until the goal is achieve.

### 7.2.1 Distance to Product

Distance to product is defined as the distance of air gap between the exit window and the scanned product. This variable can affect the dose distribution and next determine the depth of penetration inside the material because dose distribution is perpendicular to the depth of penetration.

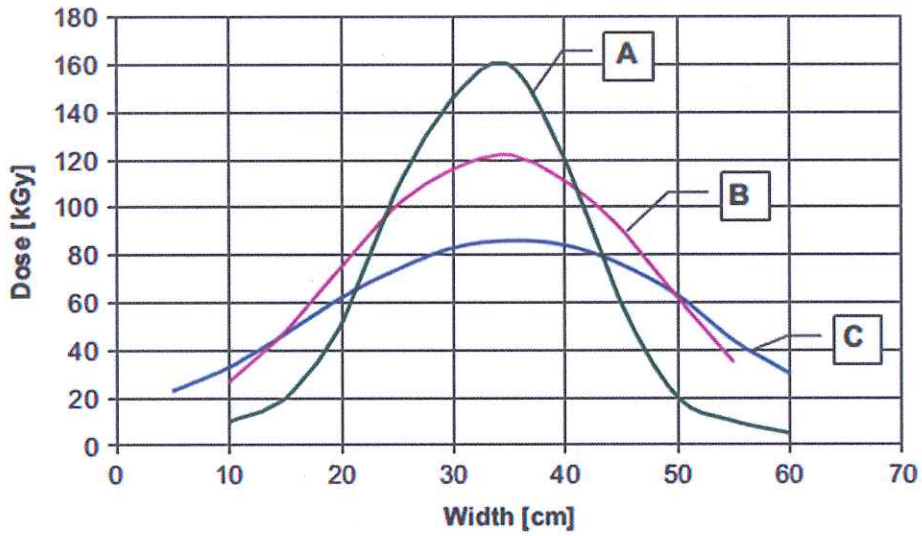


*Figure 24: Dose distribution perpendicular to irradiation zone at centre position in different distance to accelerator window* (Optimization of electron beam crosslinking of wire and cable insulation, 2012)

The graph above shows the influence of different thickness of air gap between the irradiation window and the aimed material of electron energy 1.75 MeV. Line A is the result of 25cm distance to product while B and C are 45 and 65cm. The outcome proves that decreasing of the distance to product thickness will be increase the dose distribution and hence increase the degree of crosslinking. The percentage successful of the degree of crosslinking is key to determinate the quality of the end product. Unfortunately, the problem might be arise in term of the homogeneity of the dose distribution because only the centre of

scam width will be accept the high dose compared to others. In order to overcome this situation, the geometry of the material is taken into consideration in the next section.

### 7.2.2 Geometry

The dose penetrated within the material usually is not uniform especially for the circular object like wire and cable. Most of the accelerator that have been listed in the last two chapter such as EC-Scanner, 400keV and Broadbeam LE Series used one or two sided irradiation while other used the rotation technique of conveyer under beam extraction. There are suggestion of build the 4 sided irradiation method by implement two accelerator with two sided irradiation system can improve the dose distribution homogeneity but the cost is too expensive (Optimization of electron beam crosslinking of wire and cable insulation, 2012). So, the solution to this problem is by combining the two sided irradiation method with translation and rotation technique as shown in the figure 25 below;

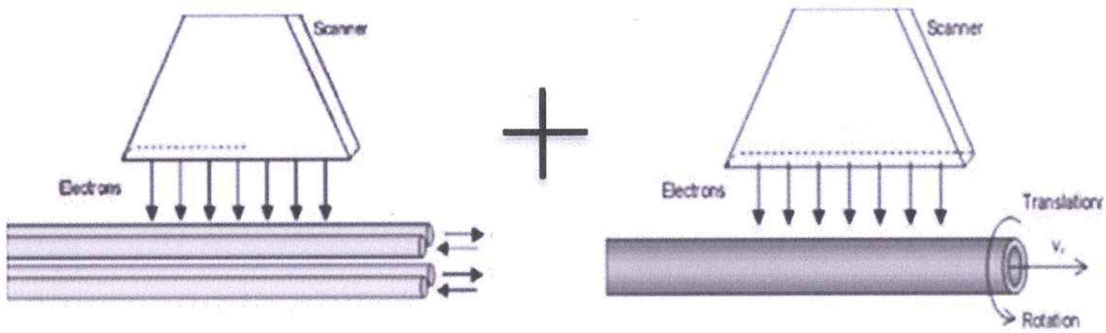


*Figure 25: Combination of the double sided irradiation with translation and rotation technique* (Electron beam crosslinking of Large Diameter PE Pipes, 2005)

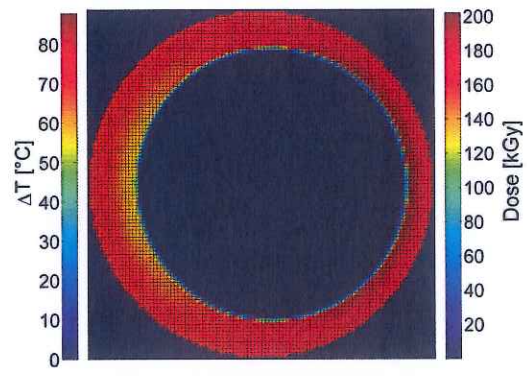


*Figure 26: Cable with LDPE jacket processed in rotation.* (Quantitative Dosimetry Simulation Tools, 2012)

The figure 26 show the distribution dose in the simulation when cable in under the rotation technique. It demonstrates the higher dose but unsymmetrical through the jacket of wire. The combining technique is proven to give the symmetrical solution of the dose distribution according to the result presented by using the Monte Carlo simulation in racetrack;

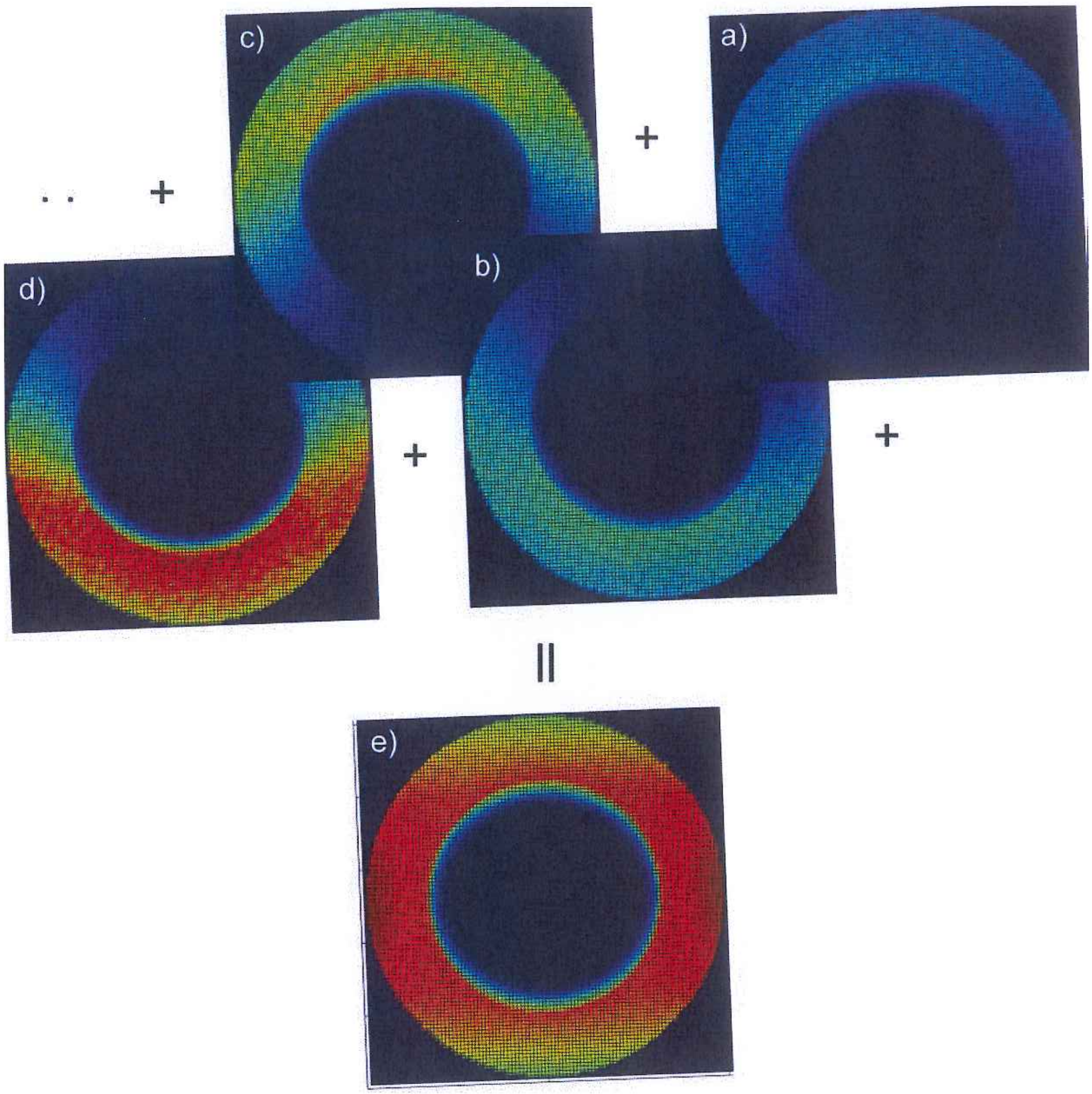


Figure 27: Example of a cable processed in figure-eight/ race track with the exact model and added up to build up the total high dose map. (Optimization of electron beam crosslinking of wire and cable insulation, 2012)

Another solution of the geometrical optimisation is by change the conveyer system of the machine as the transportation device of the product under the beam. This can be done by design the conveyer until the optimum trajectories direction of electron beam is extremely reach all position of the material. Instead of two roller of drum that commonly used in the transportations system, another two small roller can be implemented to ensure the homogeneity of dose distribution. The proposed of new development of conveyer system is shown in the diagrams below;

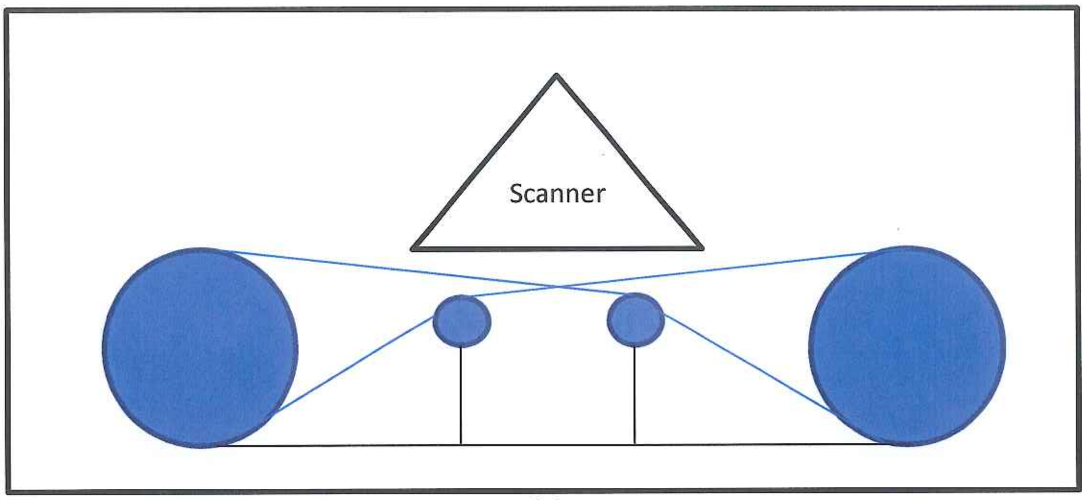


*Figure 28: The propose development of the new conveyer system*

The design of the conveyer is confident to increase the percentage of uniformity of dose distribution under the beam equipment. Angle of the material is changed when going through the small roller. In that case, the left, central and right angle of the material is ensure to receive the enough electron beam to enhance the quality of end product of crosslinking process as shown in the diagram below;

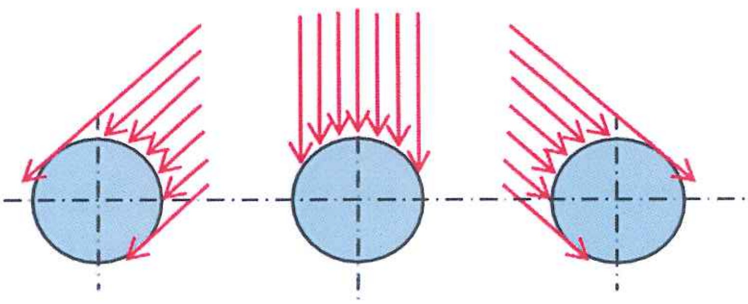

*Figure 29 : Electron trajectories of electron beam of extreme left, central and right position in the irradiation zone* (Optimization of electron beam crosslinking of wire and cable insulation, 2012)

### 7.2.3 Radio Frequency (RF) as a Power Supply Unit

All of the accelerated listed in the section 5 for crosslinking process used a direct current of power supply unit type where a constant beam is extracted while only Easy e-Beam, 800keVusing the radio frequency oscillator. RF pulsed type of accelerator is the concept of output beam is extracted by pulsed nature. This type of high voltage rectifier is convincing to reduce the power consumption according to the result of crosslinking process in Easy e-Beam machine because of the energy deposition by the DC type is less homogenous compared to the RF pulse type.

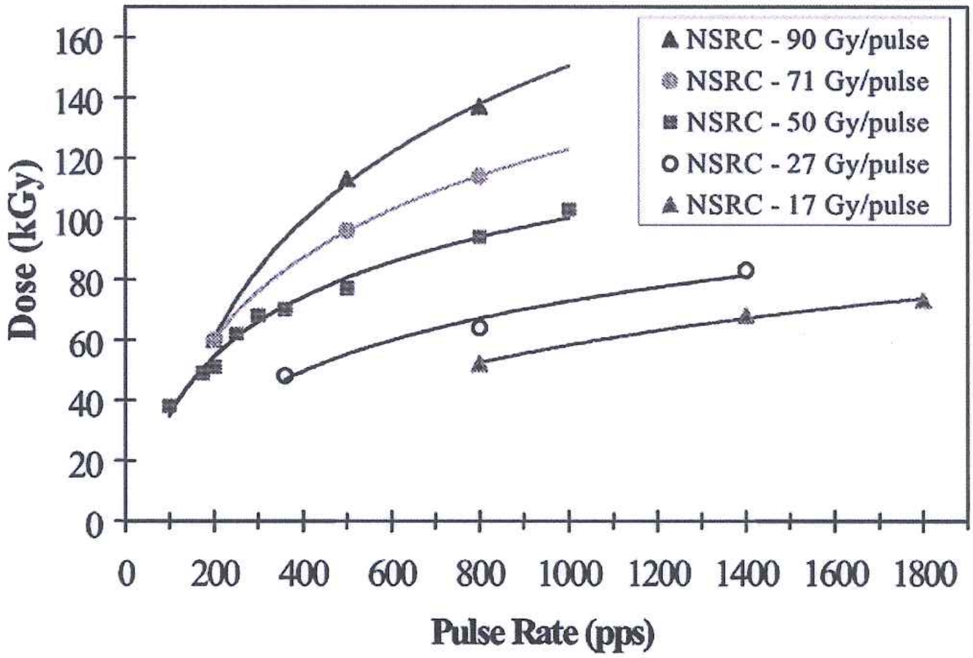


*Figure 30: Graph of absorbed dose as a function of pulse rate at different pulse level.*

(Pulsed Electron Beam Ploymerization, 2005)

The graph show the higher pulse will increase the absorbed dose of electron beam. Variation of the degree of crosslinking or polymerization process increase as the pulse rate of the beam that naturally extracting rise to the optimum level. This cannot be achieving by DC type of rectifier. As the pulse and continuous mode compared, the dose of electron beam can be controlled efficiently because of the stopping factor. The shear stress of the end product also been investigate and the result is shown below;

| Sample ID | Beam type | Residence Time (s) | Dose (kGy) | Peel (oz/1/2 in) | Shear (minutes) |
|---|---|---|---|---|---|
| 1 | continuous | 10 | 27 | 30 | 10k |
| 2 | continuous | 10 | 50 | 32.5 | 10k |
| 3 | continuous | 5 | 31 | 33.9 | 10k |
| 4 | continuous | 5 | 60 | 27.2 | 10k |
| 5 | continuous | 3.3 | 58 | 30.5 | 10k |
| 6 | continuous | 3.3 | 68 | 26.5 | 500 |
| 7 | continuous | 2.5 | 68 | 9 | 2,000 |
| 8 | pulsed | 4.6 | 59 | 32.9 | 10k |
| 9 | pulsed | 4 | 88 | 41 | 10k |
| 10 | pulsed | 3.5 | 109 | 37.3 | 10k |
| 11 | pulsed | 3.1 | 117 | 33.2 | 10k |
| 12 | pulsed | 2.5 | 150 | 32.7 | 8307 |
| 13 | pulsed | 2.3 | 170 | 31.6 | 9504 |

*Figure 31: Peel and Shear Strength Measurement for tapes made by continuous and pulse electron beam* (Pulsed Electron Beam Ploymerization, 2005)

The pulsed and continuous beam is investigated in a different condition of dose with the same sample of polymer. The conclusion arise from the table is although in a high dose, the peel and shear strength of polymer consistently high compared to the continuous beam. And the crosslinking process can be done faster according to the average residence time of pulsed beam. This give an advantage in terms of increasing of no of passes can go through under the beam in a time that will be lower the cost production and reduce the energy efficiency for overall process.

## 8.0 Conclusion

In summary, the electron beam crosslinking application has been evolved since it was invented 50 years ago. Electron beam technology became the best resolution to replace the radiation and traditional technique of crosslinking because of the environmental friendly and cost effective criteria. It is crucial to understand the system the system behind the process of electron beam crosslinking to detect the possible area that potentially can be improved. Many research and development conducted by the researcher all around the world with the same reason which is to enhance the quality of the end product for greater efficiency of the machine and lower cost of production. The first step is to test and define process plans before implemented to the actual device. So, simulation program such as Monte Carlo Simulation EBXLINK3D is great language programming to design and examine the result of the proposed suggestion of new development of the machine. The time and cost of improvement is under consideration to ensure the reliability of long term production of the machine for the future needs.

## 9.0 Acknowledgement

I would like to express my appreciation to my supervisor Dr. Kai Hock for helpful, assistance and advice throughout completing the project. Special thanks to my family and friends for their support and sprit that give me strength to finish this project. I also want to thanks to all people that have involved direct or indirectly along the way of completing my project. Your cooperation is really appreciated.

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# 11.0 Appendix

## 11.1 Project Proposal

**Title of the project**: Industrial Application of Electron Beams

**Supervisor**: Dr Kai Hock

**Aim of the project**:

A review on application of electron beams in cross linking and to identify potential areas in need of further research and development.

**Objectives of the project**:

1) To study on how electron beams are used in cross linking.
2) To research on how electron beam machines works for the application.
3) To research on possible area of development of the machines for greater efficiency and lower cost.

| Week | Goals |
|---|---|
| 1 | Project proposal discussion with the supervisors. Make a research of application of the electron beam and find the journal/papers about the application. |
| 2 | Do the report about the introduction, theory and background of the project. Hand in the risk assessment form and the proposal for the project. |
| 3 | Review the applications of electron beams in cross linking. Ensure understand the process on how beams strengthen the plastic and properties needed in the process. |
| 4 | Research the electron beam machines of that application. Identify the type, brand and the companies that made the machine. |
| 5 | Research on the physics of the machine. Description on power, voltage, electron source, lenses, focusing and other properties used on the machine. |
| 6 | Make the analysis to improve the application of electron beam in the application in terms of the energy, current, width, distribution or other properties of the beam. |
| 7 | Do some theoretical calculation to test the suggestion on improvement in order to ensure it can works on the machine. Included the cost and time of development. |
| 8 | Prepare the draft slides for the oral presentation on that week. |
| 9 | Discuss the whole project, deduce the final result of improvement of the application and start the write up of the project report. |
| 10 | Write the project report. |
| 11 | Finish the project report. Submit the finished report to the supervisors to make sure everything is done correctly. |
| 12 | Hand in the written project report. |